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Validation of a Simple Device for the Evaluation of Ankle Plantar- and Dorsi-Flexor Forces Consistent with Standard Clinical Evaluations

Giulia Rogati [1], Paolo Caravaggi [1,*], Andrea Martelli [2], Roberta Fognani [2], Alberto Leardini [1] and Massimiliano Baleani [2]

[1] Movement Analysis Laboratory, IRCCS Istituto Ortopedico Rizzoli, Via di Barbiano 1/10, 40136 Bologna, Italy; giulia.rogati@ior.it (G.R.)

[2] Medical Technology Laboratory, IRCCS Istituto Ortopedico Rizzoli, Via di Barbiano 1/10, 40136 Bologna, Italy; andrea.martelli@ior.it (A.M.); massimiliano.baleani@ior.it (M.B.)

* Correspondence: paolo.caravaggi@ior.it

Abstract: Measuring the forces produced at the ankle joint is critical to diagnose musculoskeletal pathologies. In standard clinical practice, ankle force is often assessed through manual joint manipulation and visual observation. This study introduces a simple apparatus, the Ankle Force Transducer (AFT), based on a uniaxial load cell capable of measuring ankle forces in conditions consistent with clinical evaluations. The AFT can be placed at the extremity of any examination couch to measure ankle forces in plantarflexion and dorsiflexion. The repeatability of the AFT was assessed in 30 healthy subjects across three sessions and in two knee postures. One patient with foot-drop condition was evaluated using the same apparatus. The intra-session coefficient of variation for plantarflexion and dorsiflexion forces was around 5% and 8%, respectively. The dominant leg exhibited greater forces than the non-dominant one, and the fully extended knee resulted in significantly larger forces with respect to the flexed knee ($p < 0.001$). The foot-drop patient showed a 90% reduction in dorsiflexion force in the affected limb. The AFT appears to be a user-friendly tool used to measure ankle forces, which has the potential to provide more repeatable and objective measurements of ankle forces with respect to operator-dependent evaluations.

Keywords: ankle force measurement; musculoskeletal assessment; ankle strength; instrumental evaluation; foot-drop; clinical scoring systems

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1. Introduction

Injuries and pathologies affecting muscles and joints in the lower limb are commonly assessed by physiatrists and orthopedic surgeons via visual observation and manipulation of the relevant body segments. Several musculoskeletal and neurological conditions, such as damages and pathologies of the central and peripheral nervous system, along with traumatic events and complications following surgeries, can result in insufficiency of the ankle plantarflexor and/or dorsiflexor muscles. This may lead to altered gait patterns and significant kinematic compensations in the more proximal lower limb joints, such as the knee and the hip [1]. A rather common pathology which affects the muscles in the anterior compartment of the leg is the compression or injury of the peroneal nerve. Individuals with reduced ankle plantarflexion strength typically walk more slowly and compensate at the hip and knee joints, for example, by increasing the hip extension force [2,3].

Several scoring systems for the clinical assessment of the ankle muscles' forces are available, such as the Medical Research Council (MRC) scale for muscle strength, which is based on a 0–5 scoring system [4]. This scoring system relies on the operator sensitivity in assessing the residual force of the muscles acting at the ankle either with or without the effect of gravity. In particular, the patient lies supine or sits with their ankle in neutral position and is requested to apply the maximum ankle plantar- and dorsi-flexion force against the manual resistance applied to the foot by the operator. Like other operator-based clinical scores, this scoring system is based on a limited number of discrete values, and the assessment of the degree of impairment is subjective and depends on the evaluator's experience.

Accurate assessment of muscle strength is a critical element of any physical evaluation in standard clinical practice to score the degree of impairment and to identify the most suitable treatment. It has been shown that the maximum voluntary ankle force exerted by the plantar- and dorsi-flexion muscles is affected by the knee [5] and the ankle [6] flexion angles. However, comparing ankle force data across studies is difficult since different subjects' postures—prone, supine, and sitting—have been used in the literature [7]. Indeed, a variety of apparatuses have been proposed for the objective instrumental measurement of ankle forces. Some devices are manually held [8–10] or fixed [6,9] force transducers. Rehabilitation devices, such as the AnkleBot [11] (developed at Massachusetts Institute of Technology, Cambridge, MA, USA), the Biodex System (Biodex Medical Systems, New York, NY, USA) [12], and the Prima Plus (Easytech, Florence, Italy) [5] have also been employed to assess the ankle strength properties. These devices have both advantages and disadvantages. While manually held devices are easy to use, the measurements are likely affected by the operator-dependent unstable and non-consistent positioning of the transducer with respect to the foot [8,10]. Conversely, the force transducers fixated to a stable support do not always allow for the replication of clinical evaluation conditions [9]. In addition, most of the devices currently available on the market are rather bulky and require large, dedicated rooms and do not always represent a cost-effective solution for those centers with limited resources.

Therefore, the aim of this study was to propose a simple, instrumental-based cost-effective solution to measure both ankle dorsi- and plantar-flexor forces in quasi-isometric contractions, replicating commonly used clinical evaluation methods based on the manual assessment of ankle strength. The repeatability of the measurement procedure has been assessed in a population of 30 healthy subjects with no history of foot/ankle pathologies or surgeries. In addition, a comprehensive investigation of differences in ankle muscle strength between dominant and non-dominant legs remains insufficiently explored [9], underscoring the necessity for further scientific investigation in this area. A preliminary application of the procedure was conducted on an exemplary patient with foot-drop condition.

2. Materials and Methods

2.1. Experimental Setup

A custom apparatus (Ankle Force Transducer, AFT) was designed to be placed at the end of any examination couch to measure ankle forces in quasi-isometric conditions in plantarflexion and in dorsiflexion (Figure 1). The AFT was designed in accordance with the requirements of clinical evaluation protocols to allow for the objective, instrumental-based assessment of ankle force, minimize patient discomfort and set-up time, and be compact, low-cost, and user-friendly. The AFT is comprised of an axial load cell (Mod. TS-TM 1 kN; accuracy class 0.5; AEP Transducers, Cognento, Italy) sampling at 50 Hz and fixated to an aluminum frame, allowing three translational degrees of freedom to be obtained. A battery-powered wired handheld data logger device allows for load cell zeroing and for real-time force data visualization and storage. The total cost of the present AFT was lower than EUR 2000.

Force at the forefoot is measured in quasi-isometric condition via two parallel polyethylene cylinders connected to the load cell. Since the load cell had a certified 0.5 accuracy class, the error in the measured forces with the calibrated sensor was known.

Ankle force is measured with the subject lying supine and the ankle hanging off the edge of the examination couch. Antero-posterior (i.e., the distance from the ground), medio-lateral, and cranio-caudal positions can be manually adjusted by the examiner to place the load cell axis between the first and the second metatarsal heads of the foot, while keeping the ankle in a neutral position (about 0 deg flexion). Since these adjustments may affect the consistency of the measurements, a repeatability assessment of the procedure had to be performed.

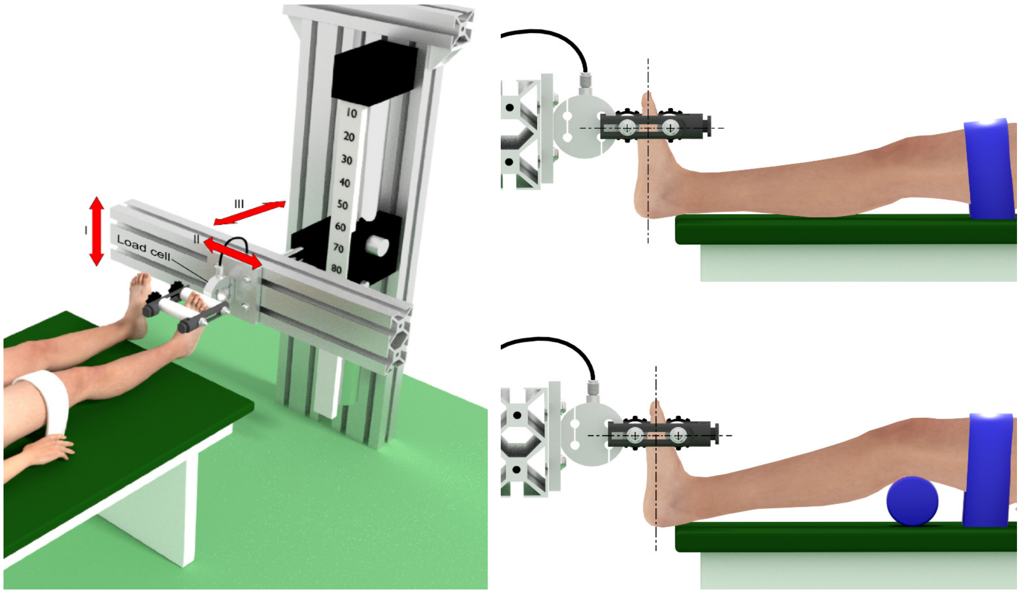

Figure 1. The ankle force measurement apparatus (AFT). (**Left**), the axial load cell fixated to an aluminum frame, allowing for three degrees of freedom to be obtained in the (I) antero-posterior, (II) medio-lateral, and (III) cranio-caudal directions. (**Right**), lateral view of the apparatus showing the knee fully extended (**top**) and flexed (**bottom**) by placing a cylinder under the joint.

2.2. Repeatability Study

Thirty healthy adults (15 F, 15 M; age 51.5 ± 6.2 years, BMI 24.5 ± 4.2 kg/m^2) were recruited and signed informed consent to participate in the experimental evaluation. The inclusion criteria were as follows: age between 40 and 60 years; absence of major foot and lower limb injuries/surgeries; absence of minor foot and lower limb injuries in the last three years.

Basic morphometric analysis of the feet was performed by using the PodoBox, a plexiglass box fitted with adhesive rulers to measure the main foot dimensions [13]. Foot length, width, and the distance between the first metatarsal head and the center of the medial and lateral malleoli were recorded for each foot (Table A1, in Appendix A).

Ankle force was acquired with the knee fully extended and with the knee flexed by around 15 deg (Figure 1, right). Straps were used to secure the leg just above the knee to limit the engagement of thigh muscles (Figure 1, see also Appendix A). Force data were collected for the ankle of both the dominant and non-dominant leg. Leg dominancy was identified by asking which leg was normally used to kick a ball [14].

In each trial, temporal profiles of force data were recorded continuously for 30 s while the participants were alternating muscle contractions in plantarflexion and dorsiflexion in quasi-isometric conditions. Verbal encouragement was used to motivate subjects to generate the maximum voluntary ankle forces. For this acquisition time, a minimum of seven plantarflexion or dorsiflexion peak of forces were acquired in each trial. Participants were allowed one minute to rest between trials to avoid muscle fatigue. The healthy subjects were assessed in three sessions about one week apart.

For each trial, the highest and lowest peak plantarflexion and dorsiflexion forces were excluded to enhance data consistency, and five measurements were used for statistical analysis. The coefficient of variation (CV, ratio between standard deviation and mean of the measurements) was calculated to determine intra-session (inter-trial) repeatability. For each participant, the CV computed for the 15 samples measured across the three sessions (five measurements times and three sessions) was used to determine the inter-session repeatability of ankle force data in each loading direction and knee condition. The effect of leg dominancy and the difference between plantar- and dorsiflexion forces were assessed via the non-parametric paired Friedman test ($\alpha = 0.05$) in both the fully extended and partially flexed knee positions. Force data were normalized to the subject's body weight.

2.3. Pilot Study

The AFT was used to measure ankle forces in one patient affected by unilateral foot-drop condition due to neurological complications following L4-L5 spinal compression (F; age 57.8 years; BMI 24.3 kg/m^2). In addition, clinical evaluation via the MRC scale for muscle strength [4] was used to score ankle force in the affected and non-affected limb by three expert clinicians. Ethical committee approval was granted for this study (#0016384, 23/12/2019).

3. Results

3.1. Repeatability Study

A total of 3600 peak forces were recorded across subjects in the three sessions. The median intra-session CV in the dominant and non-dominant leg was approximately 5% and 8% for dorsiflexion and plantarflexion, respectively, in both knee positions (Figure 2, left). The inter-session CV was generally 3–5% higher than that for intra-session (Figure 2, right). The intra- and inter-session CVs calculated for each subject in each condition are reported in the Supplementary Materials.

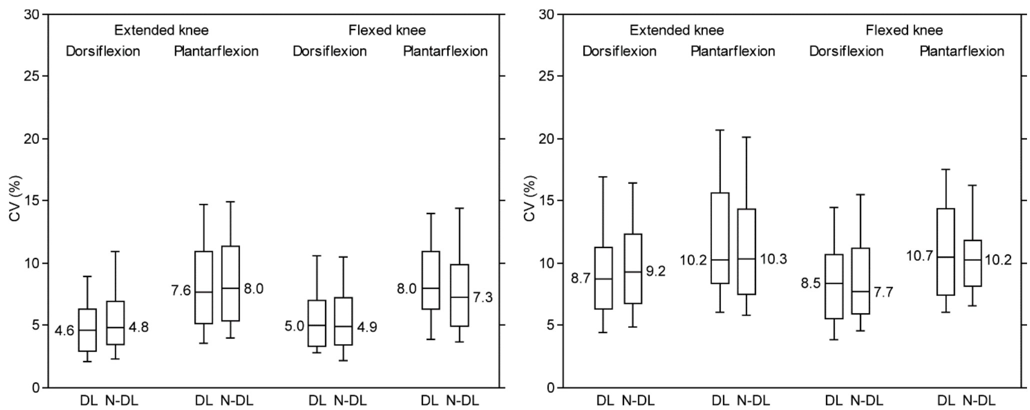

Figure 2. Repeatability of ankle force measurements. Box plots showing the 10th, 25th, 50th, 75th, and 90th percentiles of the CVs for intra-session (**left**) and inter-session (**right**) repeatability of ankle force data. DL = dominant leg; N-DL = non-dominant leg.

The median forces measured by the AFT in the healthy population ranged from 167 to 218 N across dominant and non-dominant legs in both knee postures. The ankle of the dominant leg exhibited significantly greater strength compared to the non-dominant leg regardless of the knee posture or force direction ($p < 0.001$) (Table 1). In total, 106 out of 360 comparisons showed larger ankle forces in the dominant leg by more than 10% than in the non-dominant one. Ankle forces were significantly greater in the fully extended knee posture with respect to the flexed knee ($p < 0.001$). Overall, dorsiflexion forces were significantly larger across all conditions ($p < 0.001$), with the exclusion of the dominant side with a fully extended knee ($p = 0.69$).

Table 1. AFT measurements in the healthy population. Median (10th 90th) of absolute AFT measurements [N] and normalized to body weight [%BW] across the 30 healthy participants with the extended knee and flexed knee in the dominant and non-dominant leg. Where * indicates statistically significant differences between dominant and non-dominant leg ($p < 0.001$); ^ indicates statistically significant differences between dorsiflexion and plantarflexion in the same knee posture ($p < 0.001$).

Condition.	Direction of Force	Side	AFT [N]	AFT [%BW]
Fully extended knee	Dorsiflexion	Dominant	218 (145 296) *	28.4 (11.3 35.9) *
		Non-Dominant	205 (133 281) *,^	27.8 (9.7 36.1) *,^
	Plantarflexion	Dominant	201 (123 347) *	29.5 (9.7 47.3) *
		Non-Dominant	188 (106 318) *,^	24.0 (5.4 38.6) *,^
Partially flexed knee	Dorsiflexion	Dominant	206 (128 289) *,^	29.8 (11 37) *,^
		Non-Dominant	195 (131 273) *,^	27.8 (8.8 34.7) *,^
	Plantarflexion	Dominant	178 (116 316) *,^	27.5 (7.9 45.5) *,^
		Non-Dominant	167 (114 285) *,^	24.0 (7.5 36.1) *,^

3.2. Pilot Study

The three clinicians scored 5/5 on both affected and non-affected ankles in plantarflexion according to the MRC scale for muscle strength. In dorsiflexion, the non-affected ankle was scored 5/5 by all clinicians and the affected 0/5, 0/5, and 1/5.

Figure 3 shows the temporal profile of the patient's ankle force during maximum voluntary contractions in dorsiflexion and plantarflexion with the knee fully extended. In dorsiflexion, the average ankle forces were 20 ± 3 N and 213 ± 17 N in the affected and non-affected limb, respectively. In plantarflexion, the average peak ankle forces were 210 ± 21 N and 248 ± 16 N in the affected and non-affected limb, respectively.

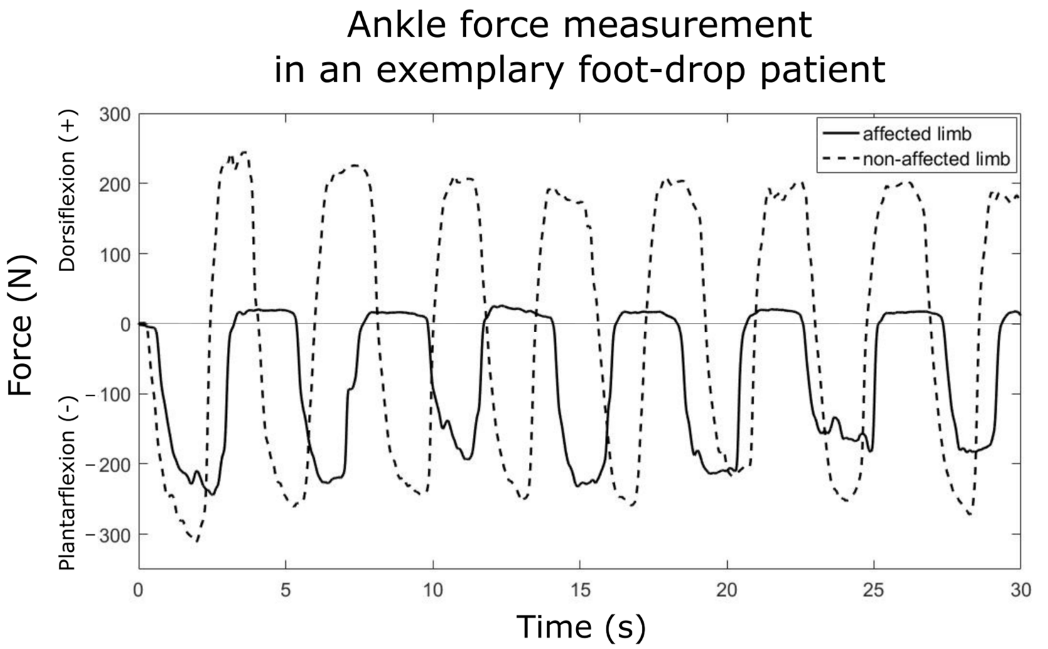

Figure 3. Ankle force measurement in a foot-drop patient. Temporal profile of the maximum voluntary plantar- and dorsi-flexion force (N) in the affected (continuous line) and in the non-affected (dotted line) in one exemplary foot-drop patient with the knee extended.

4. Discussion

One of the main functions of ankle muscles is controlling the dorsi/plantarflexion of the foot during dynamic activities. The identification of ankle muscle pathologies is crucial to obtain an accurate diagnosis and in the prescription of orthotics. In most cases, in clinical practice, the forces exerted at the ankle are assessed by clinicians via joint manipulation.

This study aimed to overcome the intrinsic limitations of such a subjective evaluation by preserving the same postural conditions normally used during physical examination.

The setup proposed in this study showed significant intra-session repeatability in measuring ankle forces, with CVs of 5% and 8% for dorsiflexion and plantarflexion, respectively. This is comparable to the intra-session repeatability of the dorsiflexion measurements reported by Geboers at al. [6]. The average inter-session CVs can also be considered acceptable, albeit around 3–5% higher than the corresponding intra-session CVs under the same conditions. The slight decrease in measurement repeatability may be explained by variations in the relative positioning between foot and AFT across different sessions in addition to physiological variations in the subject's performance. Therefore, it should be highlighted that differences in ankle force up to 10% can be due to the variability highlighted above and not to the phenomenon under investigation. Indeed, variability in ankle forces up to 10% can be considered physiological, as reported also by Moraux et al. [9] for intra-session measurements. In addition, the intra-session repeatability observed here for dorsiflexion measurements is comparable to that reported by Geboers et al. [6] (CV = 4.2 $\pm$ 3.6% and about 8% of all CVs exceeding 10%). While the proposed procedure can detect differences in ankle force greater than 16%, the appropriate repeatability of the apparatus should be assessed against the degree of accuracy needed for the specific application. Some limitations could be present when measuring ankle strength in patients with low muscle forces.

In terms of absolute forces measured by the standard uniaxial load cell comprising the device, the ankle dorsiflexion forces recorded in this study were comparable to those acquired with a similar setup [2]. Likewise, Ancillao et al. [8] observed very similar total forces applied at the metatarsal region during maximum isometric ankle plantarflexion (210 $\pm$ 39 N) and dorsiflexion (190 $\pm$ 39 N) with the knee in fully extended posture, albeit measured with a manual dynamometer. Regardless of the knee posture or ankle flexion direction, the dominant leg consistently displayed significantly greater ankle strength compared to the non-dominant leg. This was consistent with that reported by Moraux et al. [9] in a population of adult males (maximum difference of 13.6 Nm between dominant and non-dominant leg) and by Maganaris et al. [15], who observed 14% greater strength in the ankle of the dominant leg at 30 deg plantarflexion.

The ankle dorsiflexion forces measured here were compatible with the maximum voluntary ankle moments reported in the literature with the ankle in neutral position [16], and the plantarflexion forces were the highest in the fully extended knee posture. Unlike what has been reported by other studies [7], the forces in dorsiflexion were generally larger than those in plantarflexion in most conditions. However, with the extended knee, in only 55% of the recorded samples, dorsiflexion was larger than plantarflexion. Indeed, plantarflexion moments in healthy populations are usually reported to be about 3 $\div$ 4 times larger than dorsiflexion moments [7]. The lower plantarflexion forces estimated here are likely due to the supine position of the subjects and the immobilization of the thigh at the knee joint, which reduces the possible involvement of the more proximal lower limb muscles and joints. In addition, with respect to the fully extended knee posture, a flexed knee results in a greater mechanical advantage for the calf muscles and in a more stable leg, which can thus produce larger ankle forces (see Figure A1). While most of the current literature has focused on the assessment of maximum forces and moments at the ankle in different isokinetic and isometric conditions, the present study—similar to that reported by Ancillao et al. [8]—aimed to measure ankle forces by replicating the same conditions used by clinicians during manual assessments. For this reason, these experimental conditions cannot be considered suitable to measure the actual maximum ankle forces in plantarflexion. When used to assess the ankle strength deficit in a patient affected by foot-drop, the AFT allowed for objectively quantifying a reduction in ankle force in the affected limb of about 90% with respect to that in the non-affected limb. These measurements were still rather consistent across trials (CV = 17%), also considering the severe pathological condition of the exemplary patient assessed here. The AFT helps to provide an objective quantification of the neuromuscular deficit, which overcomes the subjective evaluation performed by clinicians. The measured ankle strength could also be useful to establish the right rehabilitation protocol and in the design of custom orthotic devices tailored to the patient's needs in addition to the patient's anatomy [17–19].

This study has some limitations. The proposed procedure aims to measure ankle forces by replicating the same conditions used by clinicians during manual assessments. However, the present approach does not allow for the maximum absolute force to be measured, especially in plantarflexion (see Figure A1 in Appendix A). In addition, the pilot study was carried out on one exemplary patient only. It should be highlighted that the AFT apparatus is still a prototype, it can measure ankle forces only in the sagittal plane, and proper validation should be conducted in a larger cohort of patients with different deficits of the ankle muscles before it can be used in clinical practice. This would also allow us to investigate possible correlations between clinical scores and instrumental measurements.

5. Conclusions

The instrumental measurement of ankle forces is critical to provide objective data in support of the diagnosis and clinical assessment of neuromuscular pathologies, which often rely on operator-dependent manual evaluations. While the level of repeatability should be assessed against the accuracy required for the intended use of the device, the proposed procedure involving the current AFT apparatus has shown good repeatability between trials and adequate repeatability across sessions. The current protocol has the potential to be a useful tool for the quantitative assessment of ankle strength in patients with different impairments of the ankle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14062461/s1: Supplemantary Materials—CV values for inter- and intra-session repeatability.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the "Area Vasta Emilia Centro" (#0016384, 23/12/2019).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is contained within the article and the Supplementary Materials.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Additional Details about the AFT Design

The AFT includes two additional adjustment options: the height of the leg support (I in Figure A1), which can be finely adjusted to allow different knee postures, and the horizontal position of the thigh support (II in Figure A1). A strap is provided to firmly secure the lower limb just above the knee.

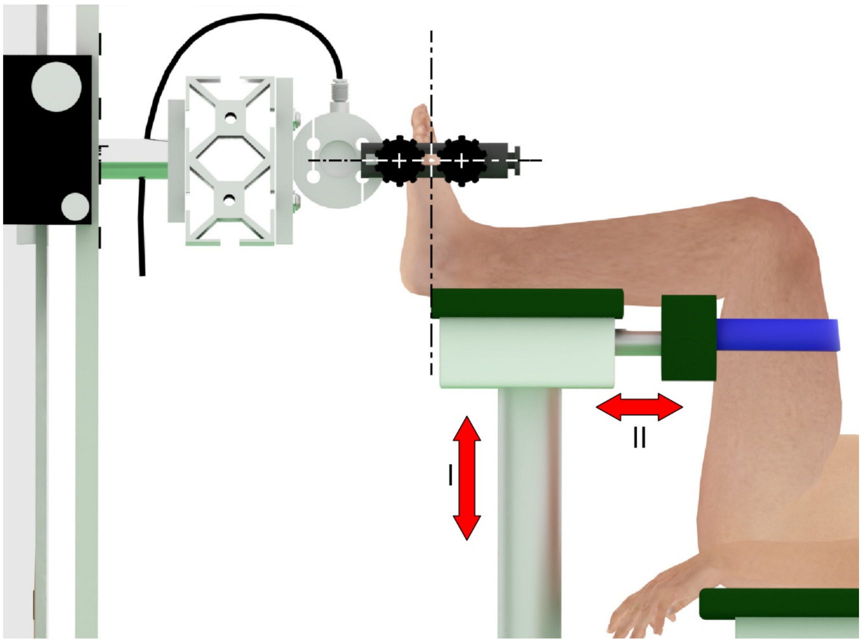

Figure A1. The additional adjustment options of the ankle force measurement apparatus. The AFT includes two additional adjustment options: the height of the leg support (I), which can be finely adjusted to allow different knee postures, and the horizontal position of the thigh support (II). In the example above, the resulting knee posture is 90 deg flexion.

The knee posture shown in Figure A1 limits the engagement of the thigh muscles. To address the aims of the present study, the participants were asked to lie down on the examination couch with their knee extended to replicate standard clinical evaluations.

Table A1. Podobox measurements. Average (±1 SD) foot dimensions measured with the Podobox in the 30 healthy subjects.

	Dominant Leg	Non-Dominant Leg
Foot length (cm)	25.4 ± 2.0	25.4 ± 2.0
Foot width (cm)	9.5 ± 0.7	9.6 ± 0.7
1st metatarsal–malleoli distance (cm)	12.6 ± 0.7	12.8 ± 0.9
1st metatarsal–malleoli distance (%foot length)	50 ± 2.0	50 ± 2.0

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